Hyperon physics with BESIII and PANDA

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working-month

CV

Educational Background

09/2014–present **Postdoctoral research**
Uppsala University of Sweden

06/2012–08/2014 **Postdoctoral research**
University of Science and Technology of China

09/2007–06/2012 **Ph.D.**
University of Science and Technology of China (USTC) and Institute of High Energy Physics, Chinese Academy of Sciences (IHEP)
Advisor: Xiaolian Wang (USTC), **Coadvisor**: Xiaoyan Shen(IHEP)
Emphasis: Experimental Particle physics,

09/2003–07/2007 **B.S. Physics**
Physics and Engineering Department, QuFu Normal University

Research experience

09/2014-present Measurement of hyperon time-like form factors at BESIII.

06/2012-08/2014 Simulation of space particle ΔE-E telescope system and performance evaluation of position-sensitive silicon detectors with four-corner readout. Supported by the Fundamental Research Funds for the Central Universities.

06/2009-02/2013 Partial wave analysis of $J/\psi \to \gamma\omega\phi$. Supported National Key Basic Research and Development Program and published in Phy. Rev. D **87**, 032008 (2013).

09/2008-08/2011 Measurements of χ_{cJ} decays to $\phi\phi$, $\omega\omega$ and $\omega\phi$. Supported by National Key Basic Research and Development Program and published in Phys. Rev. Lett. **107**, 092001 (2011).

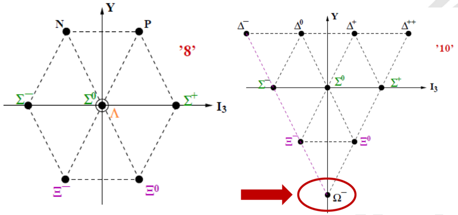
Outline

- Part I : Hyperon electromagnetic form factors with BESIII
  - Hyperon
  - Electromagnetic form factors
  - What we can do with BESIII?
- Part II : Hyperon spectroscopy with PANDA
  - Motivation
  - Prospects
- Part III : Partial wave analysis of $J/\psi \to \gamma\omega\phi$
  - Motivation
  - Partial wave analysis

Hyperon electromagnetic form factors with BESIII

Baryons and quark model

- 1950's: Elastic electron scattering on neutron ($e^- N \to e^- N$) $\to$ determine the spatial distribution of the electric current inside nucleon $\to$ not point-like
- 1960's: A multitude of new particles discovered $\to$ could not all be elementary $\to$ many of them were classified as *strange*
- 1961: Eight-fold way, organizing mesons and spin $\frac{1}{2}$ baryons into octets and spin $\frac{3}{2}$ into a decuplet as a consequence of SU(3) flavour symmetry
- 1964: Discovery of the predicted $\Omega^-(sss)$ demonstrated the success of the Eightfold way.
- 1964: Quark model (Gell-Mann and Zweig)

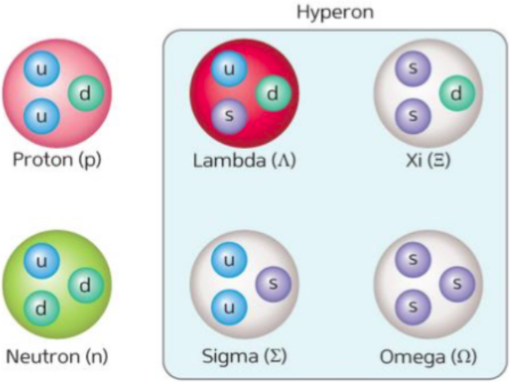


- *This is an example of how decisive hyperons have been for the development of the understanding of our microscopic world.*

Hyperons

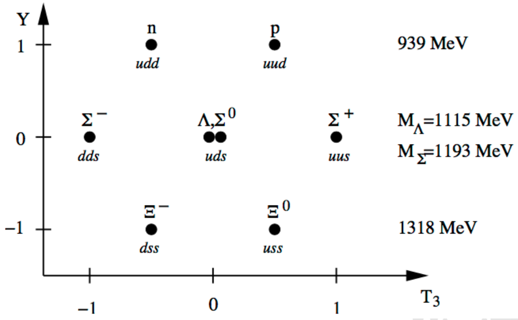
Key question:

What happens if we replace one of the light quarks in the nucleon with one or many heavier quark(s)?



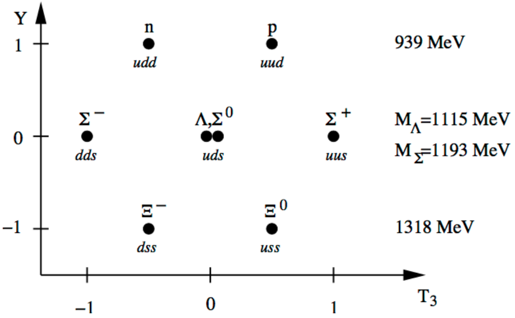
Hyperons

- Can we derive the properties of the hyperons from what we know about nucleons, *i.e.* or to which extent is SU(3) symmetry broken?



Hyperons

- Comparing different hyperons with different isospin, do the data support the diquark picture or not?
- Λ is isosinglet, it features 'good' $[ud]$ diquark correlation[1]
- Σ is isotriplet, it features 'bad' (ud).
- $\sigma(e^+e^- \to \Lambda\bar{\Lambda}) > \sigma(e^+e^- \to \Sigma^0\bar{\Sigma}^0)$



[1] R. L. Jaffe, Phys. Rep., 409 (2005)

Diquark

- Long-standing question in baryon spectroscopy: diquark substructure in baryons?
- *Diquarks are, of course, colored states, and therefore not physical.*
- It implies that our understanding of the strong interaction needs to be revised.

Electromagnetic Form Factors

- Fundamental hadron structure observable.
- Describes the deviation from the point-like case.
- Related to the charge- and magnetization density.

Elastic electron scattering

- The Rosenbluth cross section of $e^- N \to e^- N$:
  $\frac{d\sigma}{d\Omega} = (\frac{d\sigma}{d\Omega})_{Mott}\{F_1^2(Q^2) + \frac{Q^2}{4M^2}[F_2^2(Q^2) + 2(F_1(Q^2) + F_2(Q^2))^2 tan^2\frac{\theta}{2}]\}$
- $F_1(Q^2)$ and $F_2(Q^2)$ are Pauli and Dirac form factors
- Alternatively, electric and magnetic form factors:
  $G_E(Q^2) = F_1(Q^2) - \frac{Q^2}{4M^2}F_2(Q^2)$, $G_M(Q^2) = F_1(Q^2) + F_2(Q^2)$
- Electromagnetic form factors are normally studied as a function of the momentum transfer squared, $q^2 = (p_i - p_f)^2 = -Q^2$
- The EMFFs are *space-like, i.e.* $q^2 < 0$

e^+e^- annihilation

- In 1961 Cabibbo and Gatto first proposed that the EMFFs of hadrons can be studied by e^+e^- annihilation.
- The EMFFs are *time-like*

PHYSICAL REVIEW VOLUME 124, NUMBER 5 DECEMBER 1, 1961

Electron-Positron Colliding Beam Experiments

N. CABIBBO AND R. GATTO
Istituti di Fisica delle Università di Roma e di Cagliari, Italy and Laboratori Nazionali di Frascati del C.N.E.N., Frascati, Roma, Italy

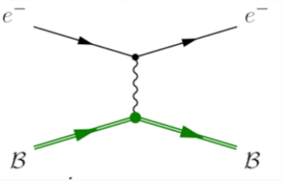
(Received June 8, 1961)

Possible experiments with high-energy colliding beams of electrons and positrons are discussed. The role of the proposed two-pion resonance and of the three-pion resonance or bound state is investigated in connection with electron-positron annihilation into pions. The existence of a three-pion bound state would give rise to a very large cross section for annihilation into $\pi^0+\gamma$. A discussion of the possible resonances is given based on consideration of the relevant widths as compared to the experimental energy resolution. Annihilation into baryon-antibaryon pairs is investigated and polarization effects arising from the nonreal character of the form factors on the absorptive cut are examined. The density matrix for annihilation into pairs of vector mesons is calculated. A discussion of the limits from unitarity to the annihilation cross sections is given for processes going through the one-photon channel. The cross section for annihilation into pairs of spin-one mesons is rather large. The typical angular correlations at the vector-meson decay are discussed.

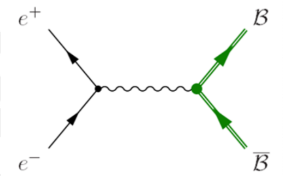
A neutral weakly interacting vector meson would give rise to a strong resonant peak if it is coupled with lepton pairs. Effects of the local weak interactions are also examined. The explicit relation between the e^2 corrections to the photon propagator due to strong interactions and the cross section for annihilation into strongly interacting particles is given.

Time-like *vs.* space-like EMFFs

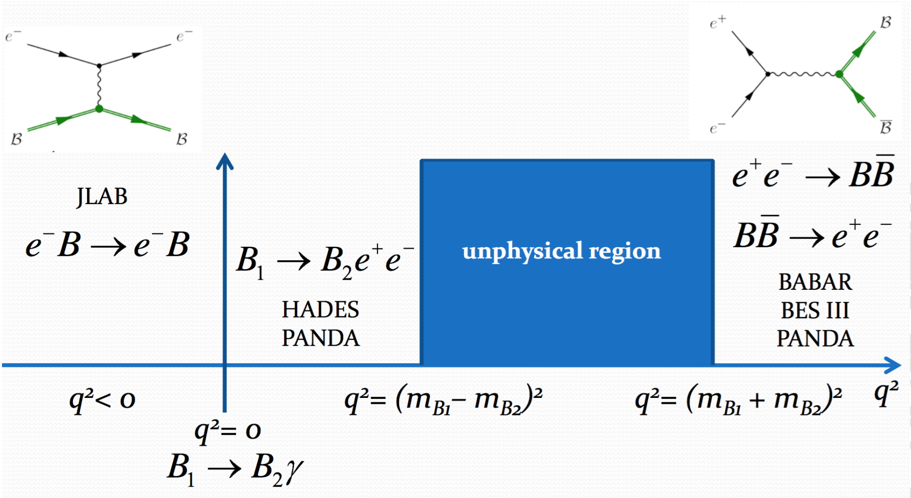
- Space-like:
  - Studied in $e^- N \to e^- N$ scattering
  - $q^2 = (p_{ie} - p_{fe})^2 < 0$
  - G_E and G_M real numbers
  - Nucleons studied since the 1960's



- Time-like:
  - $e^+ e^- \leftrightarrow B\bar{B}$
  - $q^2 \geq 4M_B^2 > 0$
  - G_E and G_M complex numbers



Time-like *vs.* space-like EMFFs



Time-like form factors

- $G_E(q^2) = |G_E(q^2)|e^{i\Phi_E}$
- $G_M(q^2) = |G_M(q^2)|e^{i\Phi_M}$
- Relative phase: $\Delta\Phi = \Phi_M - \Phi_E$

A nonzero relative phase leads to polarization of the outgoing baryons.

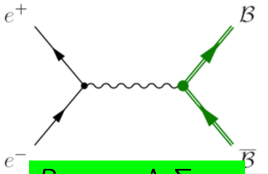
Hyperon electromagnetic form factors

- Hyperons unstable $\rightarrow$ cannot serve as target
- Only Time-Like hyperon EMFFs are experimentally accessible.
- e^+e^- collisions are currently the best way to study hyperon structure.

Measurement of TL EMFFs

Cross section: correlation between theory and experiment.

- Differential cross section:
  $\frac{d\sigma}{d\Omega} = \frac{\alpha^2\beta C}{4q^2}[|G_M(q^2)|^2(1+cos^2\theta) + \frac{1}{\tau}|G_E(q^2)|^2(sin^2\theta)]$
- Born cross section:
  $\sigma(q^2) = \frac{4\alpha^2\beta C}{3q^2}[|G_M(q^2)|^2 + \frac{1}{2\tau}|G_E(q^2)|^2]$



$B = n, p, \Lambda, \Sigma......$

$\tau = q^2/(4m_B^2)$, θ is the polar angle of baryon in the CM

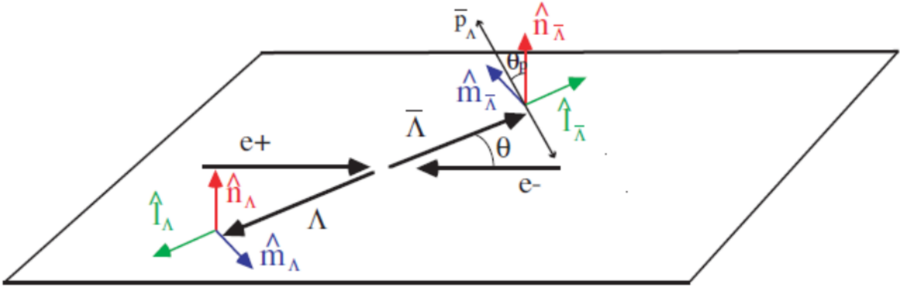
- All the formulas are valid
  - for the baryons with spin=1/2
  - assuming one photon exchange domination

Measurement of TL EMFFs

- Effective FFs: $|G(q^2)| = \sqrt{\frac{\sigma}{\frac{4\alpha^2\beta C}{3q^2}(1+\frac{1}{2\tau})}}$
- Ratio $R = |G_E/G_M|$
- $|G_M(q^2)|^2 = \frac{2\tau+1}{2\tau+R^2}|G|^2$, $|G_E(q^2)|^2 = R^2\frac{2\tau+1}{2\tau+R^2}|G|^2$

- $R = |G_E/G_M|$ measurement
- Angular dependence: $\frac{d\sigma}{dcos\theta} = N[(1+cos^2\theta) + \frac{R^2}{\tau}(1-cos^2\theta)]$
  N is the overall normalization.

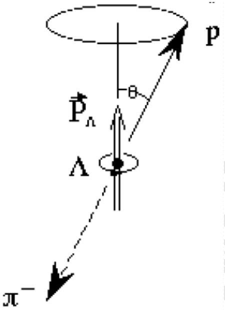
Polarization effect in the $e^+e^- \to \Lambda\bar{\Lambda} \to p\pi^-\bar{p}\pi^+$



- The n is the normal to the production plane, $\hat{n} = \hat{e}_{e^+} \times \hat{e}_{\bar{\Lambda}}$
- $\hat{l}$ is $\Lambda(\bar{\Lambda})$ momenta direction in $c.m.$ frame
- $\hat{m} = \hat{n} \times \hat{l}$
- $P_n = \frac{sin2\theta Im[G_E(q^2)G_M^*(q^2)]/\sqrt{\tau}}{|G_M(q^2)|^2(1+cos^2\theta)+\frac{1}{\tau}|G_E(q^2)|^2 sin^2\theta} \Longrightarrow$ gives modulus of $\Delta\Phi$
- $C_{lm} = \frac{sin2\theta Re[G_E(q^2)G_M^*(q^2)]/\sqrt{\tau}}{|G_M(q^2)|^2(1+cos^2\theta)+\frac{1}{\tau}|G_E(q^2)|^2 sin^2\theta} \Longrightarrow$ gives sign of $\Delta\Phi$

Measure the Λ polarization

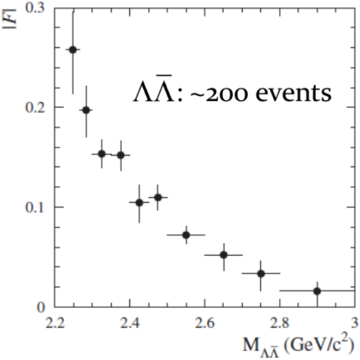
- The differential cross section of the decay proton angle: $\frac{d\sigma}{dcos\theta_p} = \frac{1}{2}(1 + \alpha_\Lambda P_n cos\theta_p)$
- The polarization can be extracted by: $P_n = \frac{3}{\alpha_\Lambda} < cos\theta_p >$
- The spin correlation of the Λ and $\bar{\Lambda}$: $C_{lm} = (\frac{9}{\alpha\bar{\alpha}}) < cos\theta_{pl} cos\theta_{\bar{p}m} >$
- α is the asymmtery parameter, $\alpha_\Lambda = 0.64, \alpha_{\bar{\Lambda}} = -0.71$(PDG2014)



Hence, the phase between the form factors would be known.

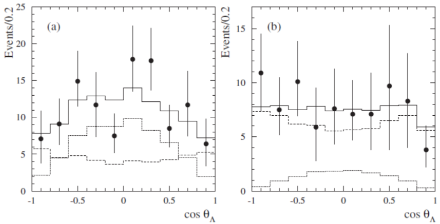
Experimental status

- Babar Collaboration:



Phys. Rev. D76, 092006(2007)

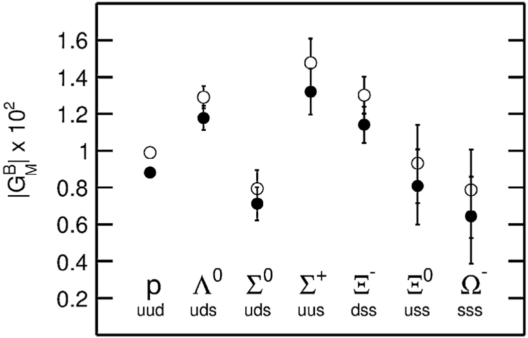
- $e^+e^- \to \gamma\Lambda\bar{\Lambda}$
- Based on very little data.
- Total error on the G_E/G_M ratio 33-100%.



- Λ polarization: $-0.22 < P_n < 0.28$
- Relative phase: $-0.76 < sin\phi < 0.98$

Experimental status

- CLEO-c: very few hyperon events @3.773GeV (15 $\sim$ 105 events)
  Phy. Lett. B739(2014)

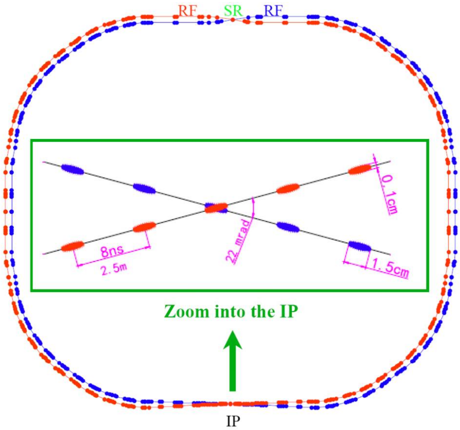


- Claim support for the diquark picture, $G_M(\Lambda) = 1.66 G_E(\Sigma^0)$, $\sigma(\Lambda)/\sigma(\Sigma^0) \approx 3$
- Far from threshold = low cross sections = small data samples = large uncertainties.
- No angular distributions → no ratio $R = G_E/G_M$ extracted → the EMFFs calculated assuming R=1 or 0.

BEPCII and BESIII

BEPCII and BESIII

BEPCII storage rings



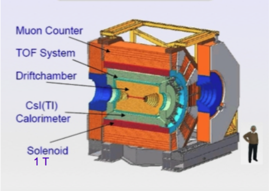
Double-ring e^+e^- collider:

- Beam energy: 1.0-2.3GeV
- Crossing angle: ± 11 mrad
- Luminosity: $1 \times 10^{33} cm^{-2} s^{-1}$
- Energy spread: 5.16×10^{-4}
- Optimum energy: $1.89 GeV$

BESIII detector

BESIII detector:

- MDC: main drift chamber (40% He + 60% propane)
- TOF: time of flight (two layers plastic scintillators)
- EMC: electromagnetic calorimeter (CsI(TI))
- MUC: muon system (resistive plate chambers)

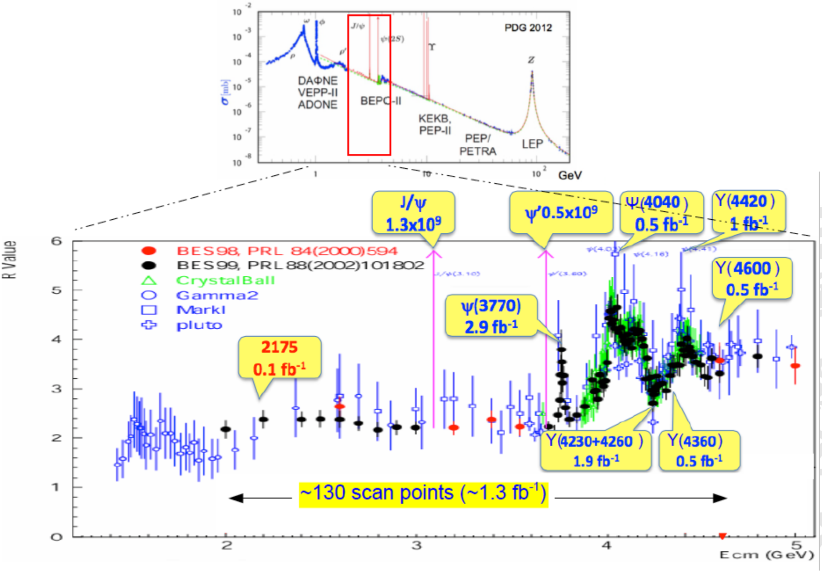


Performance:

Expt.	MDC Wire resolution	MDC dE/dx resolution	EMC Energy resolution
CLEO	$110\,\mu m$	5%	$2.2-2.4\%$
BABAR	$125\,\mu m$	7%	2.67%
Belle	$130\,\mu m$	5.6%	2.2%
BESIII	$115\,\mu m$	$< 5\%$	2.3%

Expt.	TOF time resolution
CDF	100 ps
Belle	90 ps
BESIII	68 ps (Barrel) 100 ps (ETOF)

The BESIII data sample

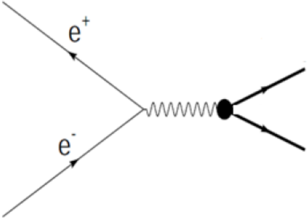


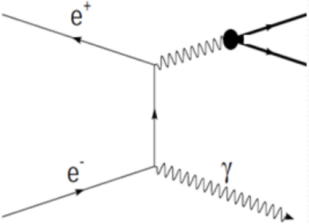
New scan data at 2015

$E_{cm}(GeV)$	Luminosity(pb^{-1})	Purpose
2.0	9.3	Nucleon FFs
2.1	11.3	Nucleon FFs
2.15	2.8	Y(2175)
2.175	10.1	Y(2175)
2.2	13.0	Nucleon FFs & Y(2175)
2.2324	11.2	Hyp Threshold ($\Lambda\bar{\Lambda}$)
2.3094	20.5	Nucleon & Hyp FFs Hyp Threshold ($\Sigma^0\bar{\Lambda}$)
2.3864	22.1	Hyp FFs Hyp Threshold ($\Sigma^0\bar{\Sigma}^0$)
2.396	64.8	Nucleon & Hyp FFs Hyp Threshold ($\Sigma^-\bar{\Sigma}^+$)
2.5	1.0	R scan
2.6444	66.3	Nucleon & Hyp FFs Hyp Threshold ($\Xi^-\bar{\Xi}^+$)
2.7	1.0	R scan
2.8	1.0	R scan
2.9	102.1	Nucleon & Hyp FFs
2.95	15.7	$m_{p\bar{p}}$ step
2.981	15.4	η_c, $m_{p\bar{p}}$ step
3.0	15.3	$m_{p\bar{p}}$ step
3.02	16.6	$m_{p\bar{p}}$ step
3.08	123.0	Nucleon FFs

- Uppsala group is responsible for hyperon EMFF measurement.

What can we do with BESIII?





	Energy Scan	Initial State Radiation
Data sample	A series of $\sqrt{s}$	one $\sqrt{s}$
q^2 range	single at each beam energy	from threshold to $\sqrt{s}$
Integrated Lum.	low at each beam energy	high at one energy beam energy

- Measure $e^+e^- \to \Lambda\bar{\Lambda}$, $\Lambda\bar{\Sigma}^0$ and $\Sigma\bar{\Sigma}$ in direct e^+e^- annihilation in the continuum between $q = 2$ and $q = 3$ GeV
- Measure $e^+e^- \to \gamma_{ISR}\Lambda\bar{\Lambda}$, $\gamma_{ISR}\Lambda\bar{\Sigma}^0$ and $\gamma_{ISR}\Sigma\bar{\Sigma}$ with ISR at $q = 3.773$ GeV, $Y(4260)$, $Y(4300)$, ...

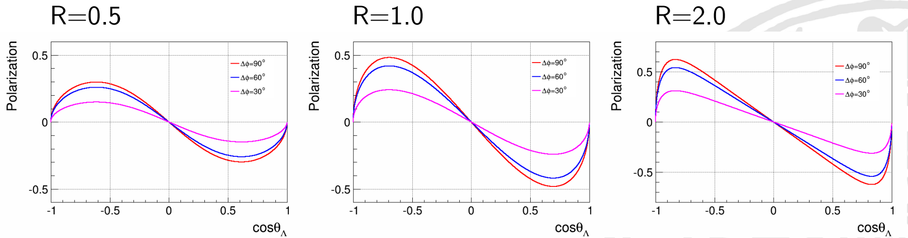
What can we do with BESIII?

- Λ
  - Effective EMFFs $|G|$, R, $|G_E|$, $|G_M|$
  - P_n as a function of scattering angle $\theta \to Im(G_E G_M^*)$
  - C_{lm} as a function of scattering angle $\theta \to Re(G_E G_M^*)$
  - $Im(G_E G_M^*)$ and $Re(G_E G_M^*) \to$ relative phase $\Delta\Phi$
- Σ
  - Effective EMFFs $|G|$, R, $|G_E|$, $|G_M|$
  - To extract relative phase we need more data

What Polarization

$$P_n = -\frac{sin2\theta Im[G_E(q^2)G_M^*(q^2)]/\sqrt{\tau}}{|G_M(q^2)|^2(1+cos^2\theta)+\frac{1}{\tau}|G_E(q^2)|^2 sin^2\theta} = -\frac{sin2\theta/\sqrt{\tau}}{(1+cos^2\theta)+\frac{R^2}{\tau}(1-cos^2\theta)} Rsin\Delta\phi$$

- As a function of $\cos\theta_\Lambda$
- The polarization has relation to R
- The polarization is proportional to $\sin\Delta\Phi$



Test with MC sample

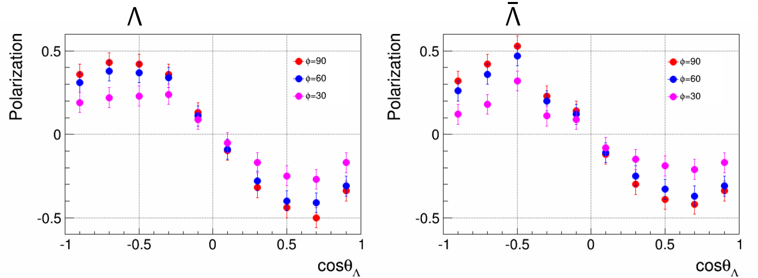
We can use Phokhara to generate events with different R and $\Delta\phi$.
MC samples:

- $R = 1.0$
- $\Delta\phi = 30, 60, 90$

Important:

- Any measurement would give a polarization close to 0 when integrating over the full scattering angle θ_Λ
- We should measure the polarization as a function of cosθ_Λ.

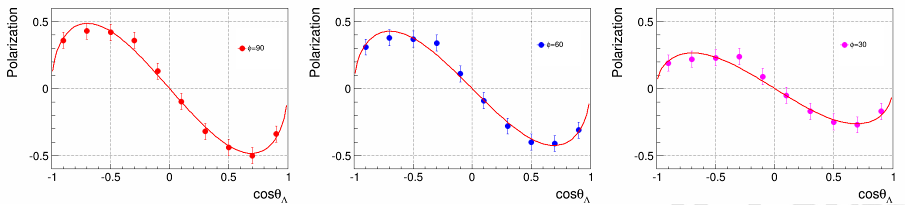
MC truth events



- MC samples are divided into 10 bins in $\cos\theta_\Lambda$
- Give ideal results
- A small difference between Λ and $\bar{\Lambda}$

Fit to polarization

Fit function: $P_n = -\frac{sin2\theta/\sqrt{\tau}}{(1+cos^2\theta)+\frac{R^2}{\tau}(1-cos^2\theta)} Rsin\Delta\phi,\ R = 1.0$



Input		Fit	
$\Delta\phi$	sin	sinϕ	χ^2/ndf
90^o	1.0	1.00±0.05	3.4/9
60^o	0.87	0.89±0.05	3.6/9
30^o	0.5	0.55±0.05	3.4/9

- I/O are consistent
- The method of moment works well

Summary of hyperon EMFFs

- Key question of hyperon, how does the structure change if light quark(s) are replaced with heavier?
- Time-like EMFFs is the best way to study hyperon structure.
- Rather unexplored territory.
- BES III is the only running experiment where this can be done.

Hyperon spectroscopy with PANDA

Hyperon spectroscopy

J^P	(D, L_N^P)	S	Octet members				Singlets
1/2+	$(56,0_0^+)$	1/2	$N(939)$	$\Lambda(1116)$	$\Sigma(1193)$	$\Xi(1318)$	
1/2+	$(56,0_2^+)$	1/2	$N(1440)$	$\Lambda(1600)$	$\Sigma(1660)$	$\Xi(?)$	
1/2−	$(70,1_1^-)$	1/2	$N(1535)$	$\Lambda(1670)$	$\Sigma(1620)$	$\Xi(?)$	$\Lambda(1405)$
3/2−	$(70,1_1^-)$	1/2	$N(1520)$	$\Lambda(1690)$	$\Sigma(1670)$	$\Xi(1820)$	$\Lambda(1520)$
1/2−	$(70,1_1^-)$	3/2	$N(1650)$	$\Lambda(1800)$	$\Sigma(1750)$	$\Xi(?)$	
3/2−	$(70,1_1^-)$	3/2	$N(1700)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	
5/2−	$(70,1_1^-)$	3/2	$N(1675)$	$\Lambda(1830)$	$\Sigma(1775)$	$\Xi(?)$	
1/2+	$(70,0_2^+)$	1/2	$N(1710)$	$\Lambda(1810)$	$\Sigma(1880)$	$\Xi(?)$	$\Lambda(?)$
3/2+	$(56,2_2^+)$	1/2	$N(1720)$	$\Lambda(1890)$	$\Sigma(?)$	$\Xi(?)$	
5/2+	$(56,2_2^+)$	1/2	$N(1680)$	$\Lambda(1820)$	$\Sigma(1915)$	$\Xi(2030)$	
7/2−	$(70,3_3^-)$	1/2	$N(2190)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	$\Lambda(2100)$
9/2−	$(70,3_3^-)$	3/2	$N(2250)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	
9/2+	$(56,4_4^+)$	1/2	$N(2220)$	$\Lambda(2350)$	$\Sigma(?)$	$\Xi(?)$	

J^P	(D, L_N^P)	S	Decuplet members			
3/2+	$(56,0_0^+)$	3/2	$\Delta(1232)$	$\Sigma(1385)$	$\Xi(1530)$	$\Omega(1672)$
3/2+	$(56,0_2^+)$	3/2	$\Delta(1600)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$
1/2−	$(70,1_1^-)$	1/2	$\Delta(1620)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$
3/2−	$(70,1_1^-)$	1/2	$\Delta(1700)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$
5/2+	$(56,2_2^+)$	3/2	$\Delta(1905)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$
7/2+	$(56,2_2^+)$	3/2	$\Delta(1950)$	$\Sigma(2030)$	$\Xi(?)$	$\Omega(?)$
11/2+	$(56,4_4^+)$	3/2	$\Delta(2420)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$

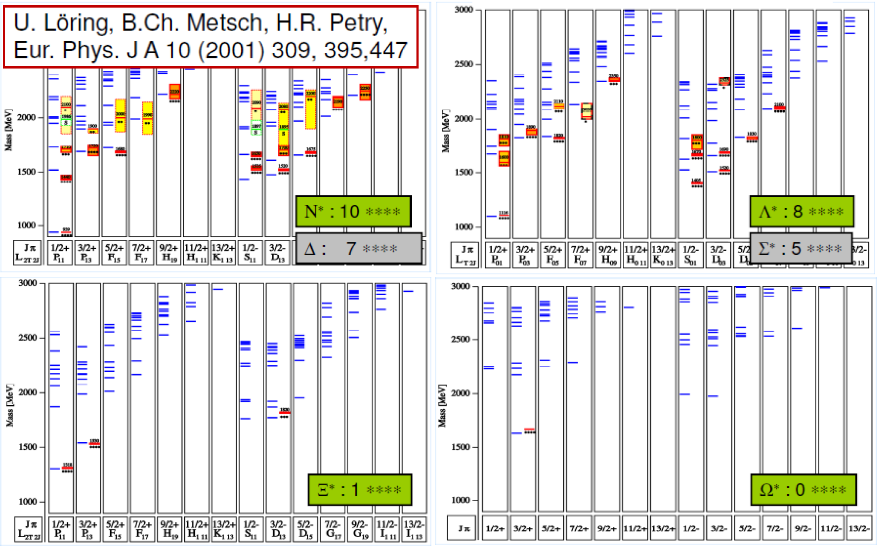
- SU(6)XO(3) classification (spin, flavor and L)
- Very scarce data bank on double and triple strangeness
- Octet Ξ^* partners of $N*$? $\to$ only a few found
- Decuplet $\Xi*$ and $\Omega*$ partners of $\Delta*$? $\to$ nothing found

Hyperon spectroscopy

J^P	(D, L_N^P)	S	Octet members				Singlets
1/2+	$(56,0_0^+)$	1/2	$N(939)$	$\Lambda(1116)$	$\Sigma(1193)$	$\Xi(1318)$	
1/2+	$(56,0_2^+)$	1/2	$N(1440)$	$\Lambda(1600)$	$\Sigma(1660)$	$\Xi(?)$	
1/2−	$(70,1_1^-)$	1/2	$N(1535)$	$\Lambda(1670)$	$\Sigma(1620)$	$\Xi(?)$	$\Lambda(1405)$
3/2−	$(70,1_1^-)$	1/2	$N(1520)$	$\Lambda(1690)$	$\Sigma(1670)$	$\Xi(1820)$	$\Lambda(1520)$
1/2−	$(70,1_1^-)$	3/2	$N(1650)$	$\Lambda(1800)$	$\Sigma(1750)$	$\Xi(?)$	
3/2−	$(70,1_1^-)$	3/2	$N(1700)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	
5/2−	$(70,1_1^-)$	3/2	$N(1675)$	$\Lambda(1830)$	$\Sigma(1775)$	$\Xi(?)$	
1/2+	$(70,0_2^+)$	1/2	$N(1710)$	$\Lambda(1810)$	$\Sigma(1880)$	$\Xi(?)$	$\Lambda(?)$
3/2+	$(56,2_2^+)$	1/2	$N(1720)$	$\Lambda(1890)$	$\Sigma(?)$	$\Xi(?)$	
5/2+	$(56,2_2^+)$	1/2	$N(1680)$	$\Lambda(1820)$	$\Sigma(1915)$	$\Xi(2030)$	
7/2−	$(70,3_3^-)$	1/2	$N(2190)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	$\Lambda(2100)$
9/2−	$(70,3_3^-)$	3/2	$N(2250)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	
9/2+	$(56,4_4^+)$	1/2	$N(2220)$	$\Lambda(2350)$	$\Sigma(?)$	$\Xi(?)$	
			Decuplet members				
3/2+	$(56,0_0^+)$	3/2	$\Delta(1232)$	$\Sigma(1385)$	$\Xi(1530)$	$\Omega(1672)$	
3/2+	$(56,0_2^+)$	3/2	$\Delta(1600)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	
1/2−	$(70,1_1^-)$	1/2	$\Delta(1620)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	
3/2−	$(70,1_1^-)$	1/2	$\Delta(1700)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	
5/2+	$(56,2_2^+)$	3/2	$\Delta(1905)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	
7/2+	$(56,2_2^+)$	3/2	$\Delta(1950)$	$\Sigma(2030)$	$\Xi(?)$	$\Omega(?)$	
11/2+	$(56,4_4^+)$	3/2	$\Delta(2420)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	

- Are the states missing
  - because they are not there
  - or because previous experiments haven't been optimal for hyperons search?
- PDG note on Ξ hyperons:
  - *"...nothing of significance on Ξ resonances has been added since our 1988 edition."*

Hyperon spectroscopy

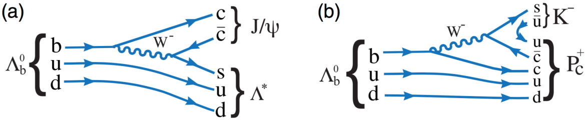


Experimental status

- Ξ^*: kaon beams at JPARC and high energy photon beams at JLAB (ongoing)
- Excited baryons also could be studied in charmonium (J/ψ and $\psi(2S)$) decays, but count rates for multi-strange resonances are very small.
- The prospects with currently running facilities for heavier double-strange Ξ^* hyperons are scarce and for triple-strange Ω non-existent.
- This is in contrast to the spectroscopy of bottom (b) and charmed (c) baryons is a very active field of research today thanks to numerous B-factories like BaBar, BELLE and LHCb.

Experimental status

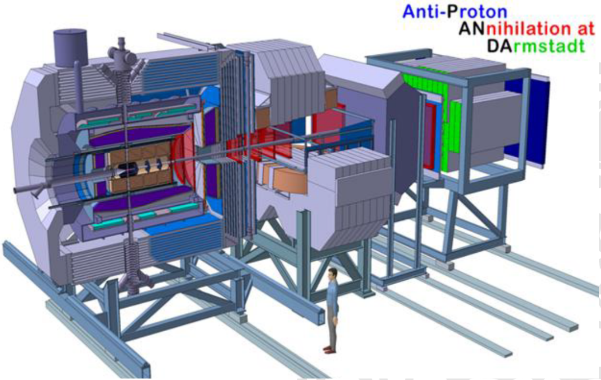
- LHCb observed two pentaquark states $P_c^+(4380)$ and $P_c^+(4450)$ in the invariant mass of $J/\psi p$ in the decay of $\Lambda_b^0 \to J/\psi K^- p$. (PRL 115, 072001 (2015))



- However, their analysis rely on the understanding of Λ^* hyperons where the experimental knowledge is scarce.
- Future discovery of additional Λ^* hyperons, or even the confirmation of the one-star states in the PDG would change the parameters of the two pentaquark states.

Prospects for PANDA

- Antiprotons from HESR with momenta 1.5 -15 GeV/c.
- Unpolarised beam and target
- Near 4π coverage
- Good momentum and vertex resolution.
- PID
- EM calorimetry



Prospects for PANDA

- Large cross section for $p\bar{p} \to \bar{Y}Y^*$
  - $p\bar{p} \to \bar{\Xi}\Xi \approx \mu b$
  - $p\bar{p} \to \bar{\Omega}\Omega \approx$0.002-0.06$\mu b$

Study excited states of

- double-strange hyperons (Ξ^*)
- triple-strange hyperons (Ω^*)
- charmed hyperons (Λ_c^*, Σ_c^*)
- hidden-charm nucleons ($N_{c\bar{c}}$)
- non-strange baryons (N^*)
- single-strange hyperons (Λ^*, Σ^*)

- PANDA is a strangeness factory.
- PANDA fills a gap in the strange sector.

Prospects for PANDA

- Partial wave analysis is quite useful tool to study hadron spectrum.
- We will work on developing PWA tools for hyperon spectroscopy before the commissioning of PANDA.

Partial Wave Analysis of $J/\psi \rightarrow \gamma\omega\phi$

Motivation

J/ψ radiative decay

- An ideal laboratory to search for glueball

$J/\psi \to \gamma VV, (V = \omega, \phi, \rho)$

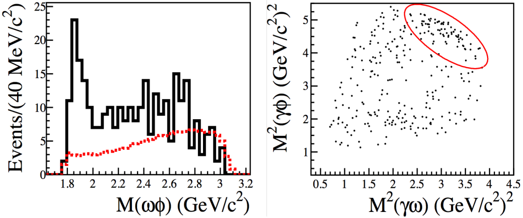
- Signatures of gluonic bound states
- Pseudoscalar enhancements in $\omega\omega$, $\phi\phi$ and $\rho\rho$ observed

$J/\psi \to \gamma\omega\phi$

- Doubly OZI suppressed decay
  - Production rate should be suppressed relative to $J/\psi \to \gamma\omega\omega$ or $J/\psi \to \gamma\phi\phi$ by at least one order of magnitude.
- An anomalous enhancement, $X(1810)$ observed by BESII

First observation of $X(1810)$ at BESII

2006: BESII observed an anomalous enhancement near the $\omega\phi$ threshold. (Phys. Rev. Lett. 96(2006)162002)



$X(1810)$:

$J^{PC} = 0^{++}$

$M = 1812^{+19}_{-26} \pm 18\,\mathrm{MeV}/c^2$

$\Gamma = 105 \pm 20 \pm 28\,\mathrm{MeV}/c^2$

$Br. = (2.61 \pm 0.27(stat) \pm 0.65(syst)) \times 10^{-4}$

$X(1810)$'s mass different from e.g. $f_0(1710)$, $f_0(1790)$.

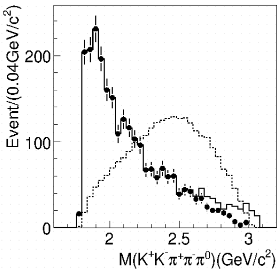
Possible interpretations:

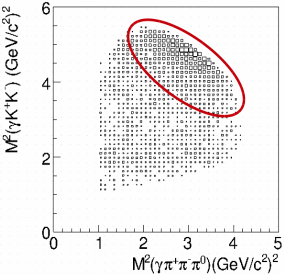
- a tetraquark, a hybrid, a glueball,
- a dynamical effect arising from intermediate meson rescattering,
- a manifestation of the $f_0(1710)$ below threshold,
- a cusp of an attracting resonance.

Neither of these interpretations were confirmed nor ruled out by experiment.

In 2009, BELLE Collaboration studied $B^\pm \to K^\pm\omega\phi$ and observed nothing obvious.

A similar enhancement at BESIII

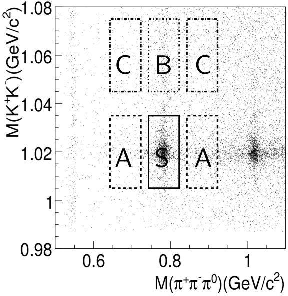


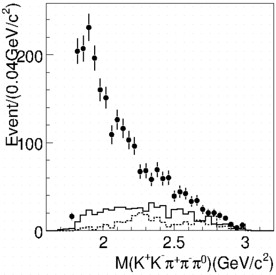


$X(1810)$:

- $J/\psi \to \gamma\omega\phi$ revisited
- 4 times more data
- Similar enhancement observed
- Invariant mass distribution very different from phase space
- Threshold structure visible in the Dalitz plot

Background study





- S: $\omega\phi$ signal region
- A: ω sideband region
- B: ϕ sideband region
- C: corner region

- Solid line: background sideband
- Dashed line: inclusive J/ψ decays.

No enhancement near $\omega\phi$ threshold from background.

Partial Wave Analysis(PWA)

Here, decay processes: $J/\psi \to \gamma X$, $X \to \omega\phi$, $\omega \to \pi^+\pi^-\pi^0$, $\phi \to K^+K^-$

- X: J^{PC} unknown, maybe $0^{++}, 1^{++}, 2^{++}, 1^{-+}$.....
- Theoretically, each possible partial wave amplitude:

$$A^i = A_{prod} BW^X_{\omega\phi} A_{decay}, \tag{1}$$

i: different J^{PC}
A_{prod}: how does X come
A_{decay}: how does X decay
$BW^X_{\omega\phi} = 1/(M^2 - s - iM\Gamma)$, M: X's mass, Γ: X's width

- A^i is unobservable
- But, total differential cross section is observable

$$\frac{d\sigma}{d\Phi} = |\sum A(J^{PC})|^2, \tag{2}$$

We can extract magnitudes and phases, M and Γ by an unbinned Maximum likelihood fit of $\frac{d\sigma}{d\Phi}$.

Maximum likelihood

- Likelihood function:
  - Probability P of the ith event:

$$P(\xi_i) = \frac{\omega(\xi_i)\epsilon(\xi_i)}{\int d\xi \omega(\xi)\epsilon(\xi)} \tag{3}$$

ξ_i: four-momentum of γ, K^+, K^-, π^+, π^- and π^0
$\omega(\xi_i) \equiv (\frac{d\sigma}{d\Phi})_i$: probability density
$\epsilon(\xi_i)$: detection efficiency

  - For N events, the likelihood is:

$$\mathcal{L} = \prod_{i=1}^{N} P(\xi_i) = \prod_{i=1}^{N} \frac{\omega(\xi_i)\epsilon(\xi_i)}{\int d\xi \omega(\xi)\epsilon(\xi)}. \tag{4}$$

- Log-likelihood: Minimize $\mathcal{S} =$ -$\ln\mathcal{L}$
- Minimization package FUMILI
- Background from sidebands have opposite sign correspond to data of log likelihood

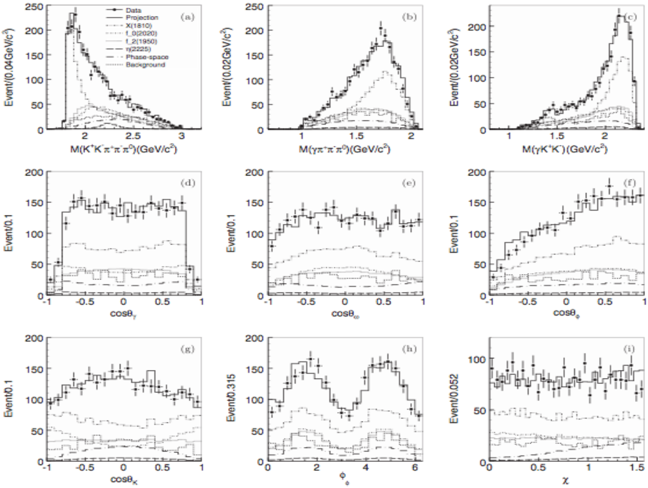
The best solution of the PWA fit

Table: Results from the best PWA fit solution.

Resonance	J^{PC}	$M(\mathrm{MeV}/c^2)$	$\Gamma(\mathrm{MeV}/c^2)$	Significance
$X(1810)$	0^{++}	1795 ± 7	95 ± 10	$> 30\sigma$
$f_2(1950)$	2^{++}	1944	472	20.4σ
$f_0(2020)$	0^{++}	1992	442	13.9σ
$\eta(2225)$	0^{-+}	2226	185	6.4σ
non-resonant	0^{-+}	—	—	9.1σ

- Five components in the best PWA fit.
- The spin parity of the $X(1810)$ is 0^{++}.
- The statistical significance of the $X(1810)$ is more than 30σ.
- The masses and widths for the $f_2(1950)$, $f_0(2020)$ and $\eta(2225)$ are fixed to their PDG values.

Comparisons between data and PWA fit



Variable	$M(K^+K^-\pi^+\pi^-\pi^0)$	$M(\gamma\pi^+\pi^-\pi^0)$	$M(\gamma K^+K^-)$	θ_γ	θ_ω	θ_ϕ	θ_K	ϕ_ϕ	χ
χ^2	44.4	36.4	42.4	24.2	12.4	28.2	18.2	26.4	51.0
ndf	40	35	40	20	20	20	20	20	30
χ^2/ndf	1.11	1.04	1.06	1.21	0.62	1.41	0.91	1.32	1.70

Additional fits with different assumptions

- Components in the best fit
  - Different J^{PC} of the $X(1810)$, the nonresonant component.
  - Different 0^{++}, 2^{++} and 0^{-+} components.
  - Different combinations of additional states.
- Resonance parametrization: Flatté formula describe the structure $X(1810)$. Test two cases:
  - With $g_{\omega\phi} = 1$, $g_{KK} = 0$
  - with $g_{\omega\phi} = 0.5$, $g_{KK} = 0.5$

- First systematic error: Difference between the best and worst solution
- Second systematic error: Difference between resonance resonance parametrization

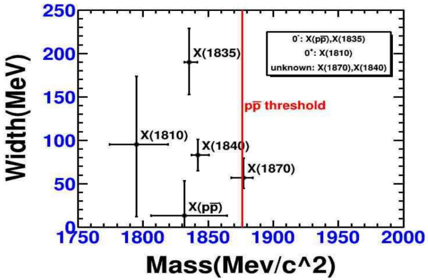
Summary of the $X(1810)$

The $X(1810)$:

- $M = 1795 \pm 7(\text{stat})^{+13}_{-5}(\text{syst}) \pm 19(\text{mod})\ \text{MeV}/c^2$
- $\Gamma = 95 \pm 10(\text{stat})^{+21}_{-34}(\text{syst}) \pm 75(\text{mod})\ \text{MeV}/c^2$
- $\mathcal{B}(J/\psi \to \gamma X(1810)) \times \mathcal{B}(X(1810) \to \omega\phi) =$ $(2.00 \pm 0.08(\text{stat})^{+0.45}_{-1.00}(\text{syst}) \pm 1.30(\text{mod})) \times 10^{-4}$

- Our results are consistent within errors with those from the BESII experiment.
- The large measured branching fractions ($\sim 1/2$ of $\mathcal{B}(J/\psi \to \gamma\phi\phi)$) is surprising and interesting.

Comparison of BESIII observation



- Based on 225M J/ψ event sample.
- Are they the same particle?
- It is crucial to identify them.

$X(18??)$ at BESIII

- $X(1860)$ in $J/\psi \to \gamma p\bar{p}$ (PRL 108, 112003 (2012))
- $X(1835)$ in $J/\psi \to \gamma\pi^+\pi^-\eta'$ (PRL 106, 072002 (2011))
- $X(1870)$ in $J/\psi \to \omega\eta\pi\pi$ (PRL 107, 182001 (2011))
- $X(1840)$ in $J/\psi \to \gamma 3(\pi^+\pi^-)$ (PRD 88, 091502 (2013))
- $X(1810)$ in $J/\psi \to \gamma\omega\phi$ (PRD 87, 032008 (2013))

Summary

- This is a common strategy when you don't understand a system: make a small change and see how the system reacts.
- In this case we ask ourselves: "*What happens if you replace one of the light quarks in a nucleon, with a heavier one?*".
- This is the fundamental question in hyperon physics.

- Two aspects of hyperon physics: hyperon EMFFs and hyperon spectrum.
- These two pillars represent a new generation of hyperon experiments which can take our understanding of the microscopic world to the next level.

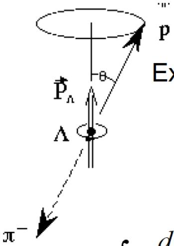
Thank you for your attention!

Method of moment

Method of Moments

The expectation value or the moment of a function *g(x)* can be written

$$\langle g(x)\rangle = \int_{\Omega} g(x) f(x\,|\,\theta)\,dx$$



where *f(x|θ)* is a probability density function.

Example: Λ hyperon with polarisation P_n decaying into $p\,\pi^-$. Then

$$f(\theta_p\,|\,P_n) = \frac{dN}{d\cos\theta_p} \propto 1 + \alpha_\Lambda P_n \cos\theta_p$$

and thus

$$\langle \cos\theta_p \rangle = \int \frac{dN}{d\cos\theta_p} \cos\theta_p\, d\cos\theta_p = \int (1 + \alpha_\Lambda P_n \cos\theta_p) \cos\theta_p\, d\cos\theta_p = \frac{\alpha_\Lambda P_n}{3}$$

which means that the polarisation can be expressed as $P_n = \dfrac{3}{\alpha_\Lambda} \langle \cos\theta_p \rangle$